Captive-Carry Flight Demonstration of an Inert Test Rocket Using a Business Jet as an Air Launch Platform

June 27, 2018

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Agenda

- **Purpose: discuss the Armstrong airworthiness process and the work required to clear the GO1 Inert Test Article for captive carry flights**

- **Historical Perspective**
- **Generation Orbit Overview**
- **Project Objectives**
- **AFRC Airworthiness Process**
- **Project Timeline**
- **C-20 and ITA Description**
- **UAVSAR vs ITA**
- **Flight Test Plan**
- **Discipline Analysis**
- **Instrumentation and Data Displays**
- **Ground Testing**
- **Flight Testing**
- **Conclusions and Project Challenges**

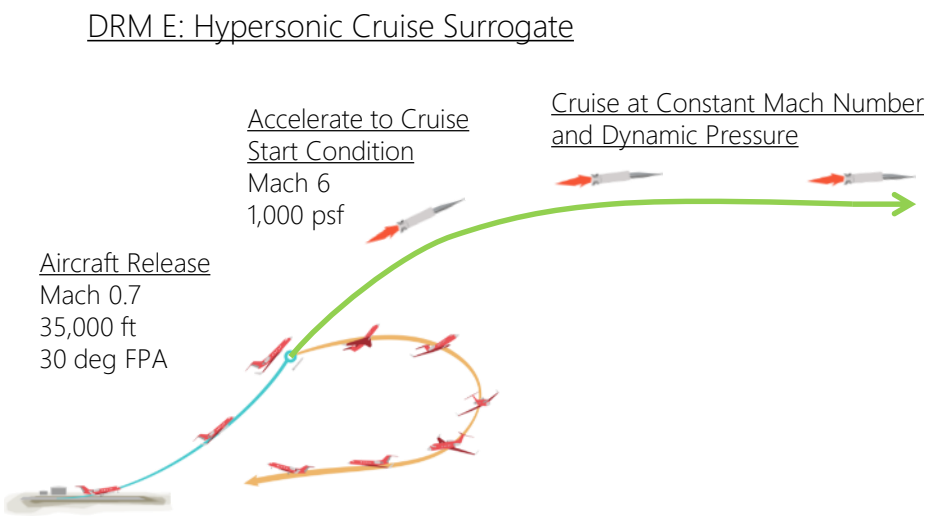
Historical Perspective

- **Past NASA Air Launch Projects:**
  - X-15
  - F-104 Air-Launched Sounding Rocket
  - Lifting Body Research
  - B-52/Pegasus air launches
  - X-37/X-40
  - X-43 Hypersonic Research

Kelly, J., et al. "Motivation for Air-Launch: Past, Present, and Future", AIAA SPACE and Astronautics Forum and Exposition, AIAA SPACE Forum.

GO1-Rocket Vehicle

- **GOLauncher 1 (GO1) is a high-speed flight testbed for research and development of hypersonic systems**
- **Capable of reaching speeds up to Mach 7 with a test payload attached**
- **GO1 development is supported by key partnerships at NASA and the US Air Force**
- **Operated from Cecil Spaceport in Jacksonville, FL under FAA/AST launch license**
- **Flight is planned for 2019**



GO1 Inert Test Article (ITA)

- In late 2015, Generation Orbit Launch Services, Inc. (GO) was awarded an opportunity to work with NASA AFRC through a Space Technology Announcement of Collaborative Opportunity
- GO1-ITA was designed to replicate the Outer Mold Line (OML) and mass properties of the empty configuration of the Generation Orbit Launcher 1 Rocket Vehicle
- The ITA weight was 1200 lb and the rocket vehicle is designed to be 2700lbs
- Project was to act as a risk reduction for the GOLauncher 1 (GO1) project

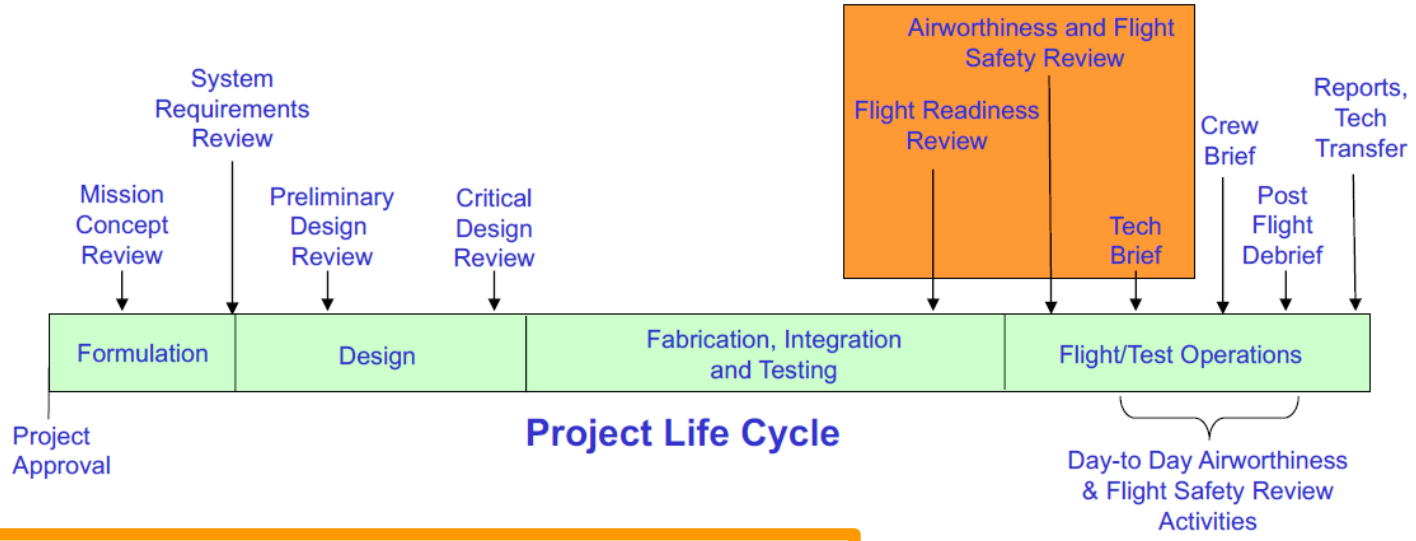
GO1 Inert Test Article (ITA)

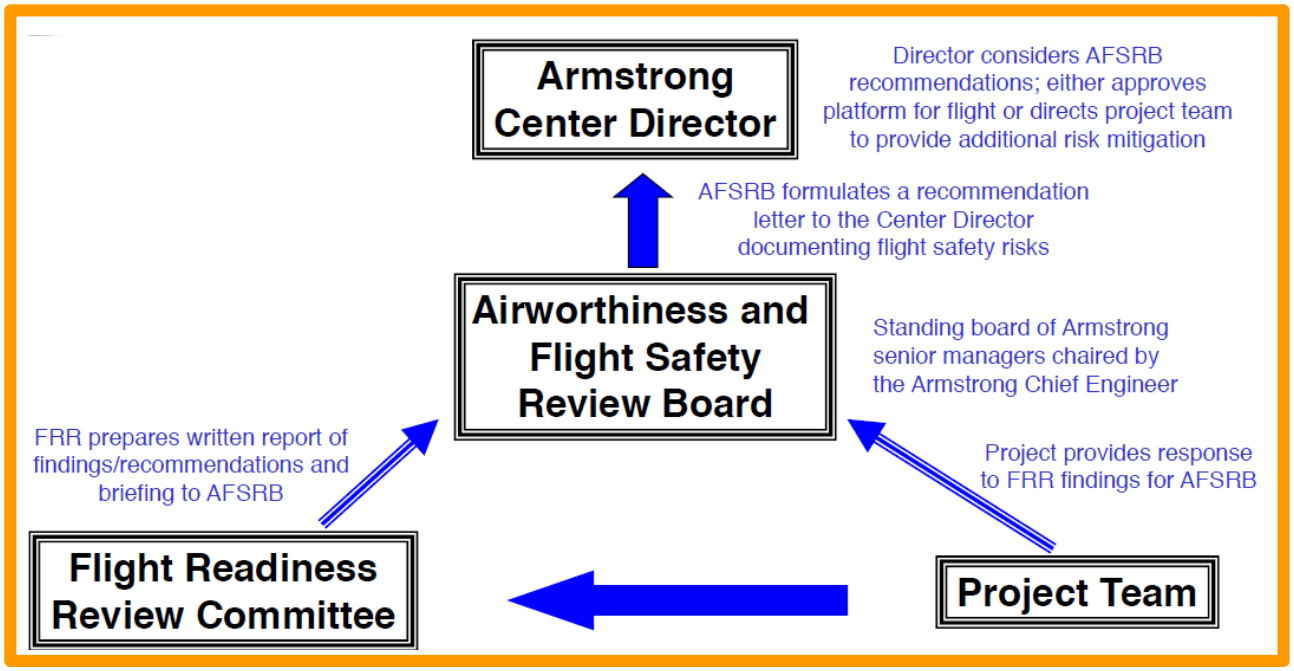
- **Original ACO scope included a feasibility assessment for a flight test using the NASA C-20 A/C as a carrier platform for a release flight of the full weight ITA**

- **Resultant test objectives included:**
  - Demonstrating aircraft performance, handling qualities, aborted release maneuver of light-weight ITA, and quantifying flight loads

- **Project requirements included:**
  - Performing aerodynamics, loads, dynamics, and controls analyses to clear the test configuration consisting of the C-20A airframe, stores rack, and ITA for a captive carry flight test
  - Performing integration between the ITA and the NASA C-20A aircraft
  - Performing captive carry flight tests demonstrating the launch abort maneuver

AFRC Airworthiness Process

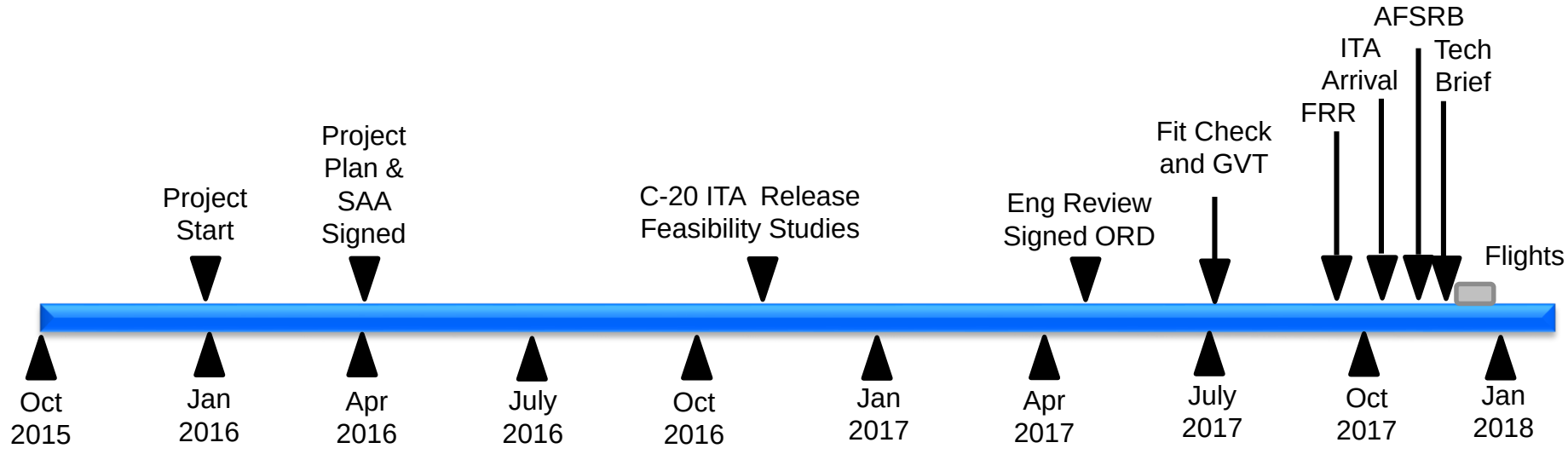




Post Tech-Brief – The project Chief Engineer works directly with the AFRC Chief Engineer to provide project status

Project Schedule

- **The effort to substantiate the airworthiness of the aircraft, pylon, and ITA capability for a captive carry flight simulating an aborted launch and recovery maneuver began in earnest beginning of 2017**
- **The project completed the full AFRC briefing cycle in December 2017**

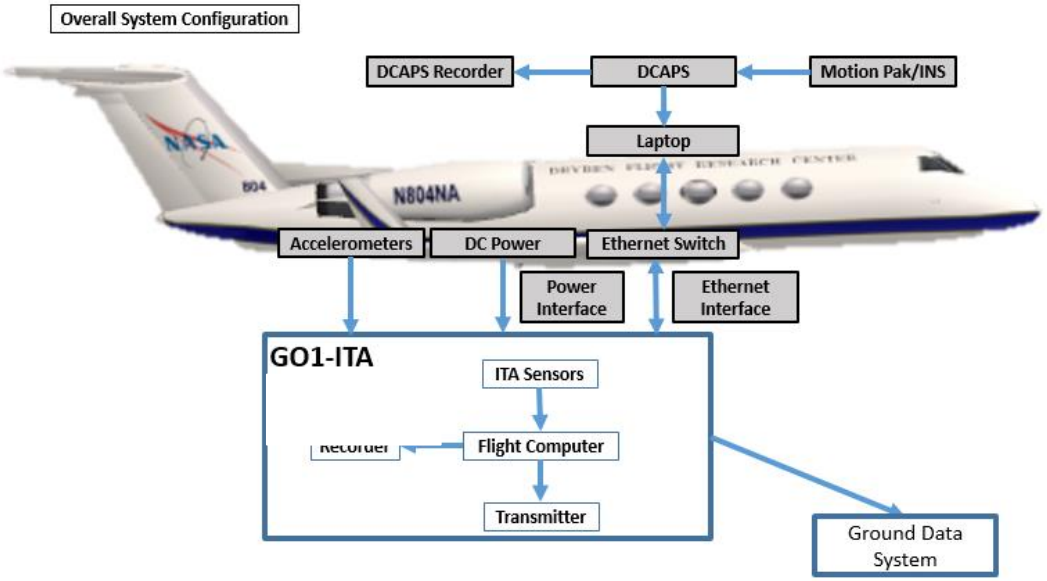


C-20 and ITA Description

- **The NASA 502 C-20 is the military version of the Gulfstream GIII, a twin-turbofan, swept-wing, business jet built by Gulfstream Aerospace Corporation**

- **The service ceiling of the C-20 is 45,000 ft, maximum speed is 340 Knots Calibrated Air Speed (KCAS) and a maximum Mach number of 0.85**

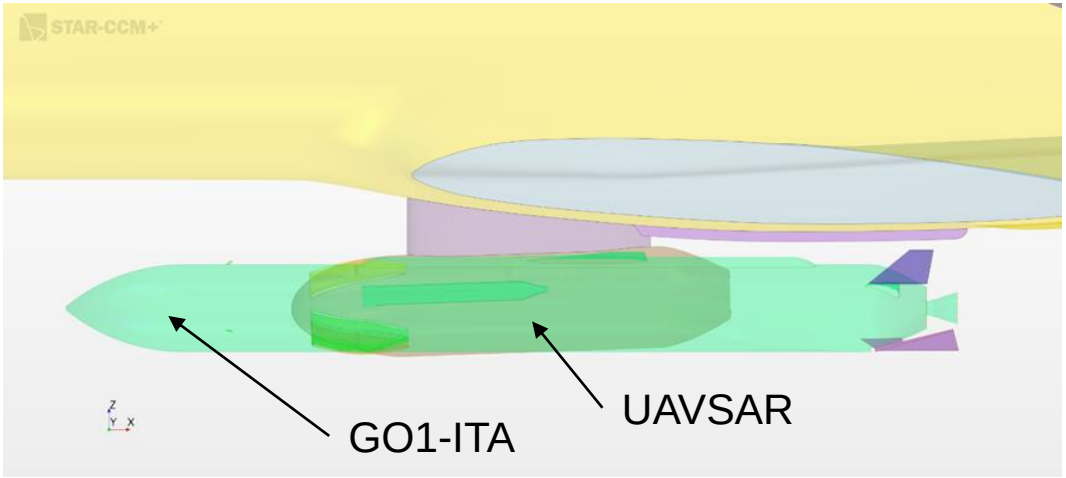
- **ITA structure consisted of a composite fuselage and a metallic wing and control surfaces**



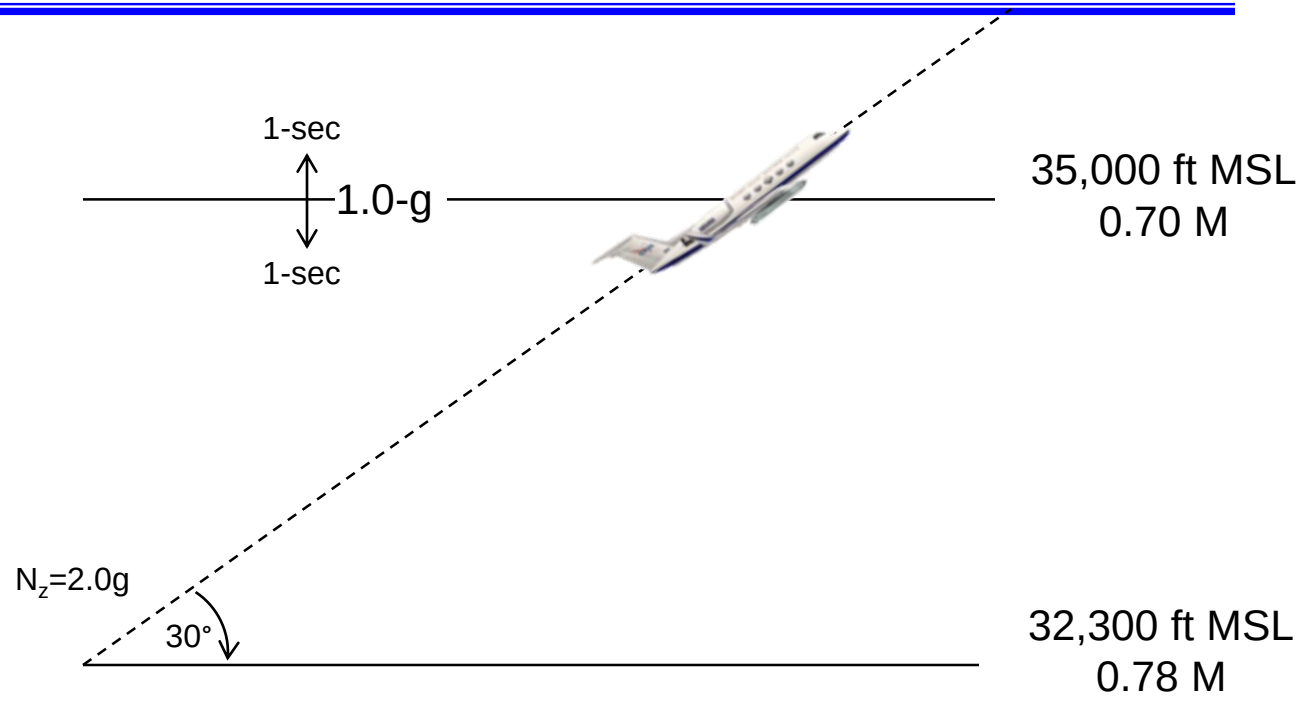
UAVSAR vs ITA

- **The NASA Unmanned Aerial Vehicle Synthetic Aperture Radar (UAVSAR) is a pod mounted earth science instrument fielded by the NASA Jet Propulsion Laboratory**
- **The UAVSAR pod and pylon were exclusively designed and flight tested for use with the NASA C-20 in 2006-2008**
- **The UAVSAR pylon design specifications were used to define the flight envelope for the GO1-ITA flight tests**

	UAVSAR	ITA
Length (in.)	129.6	262.8
Diameter (in.)	30	25.9
Mass (lbs.)	1,200	1,206.8
Ixx (lb-in^2)	115,558	204,318
Iyy (lb-in^2)	905,584	5,754,859
Izz (lb-in^2)	899,509	5,747,653



Desired Release Condition

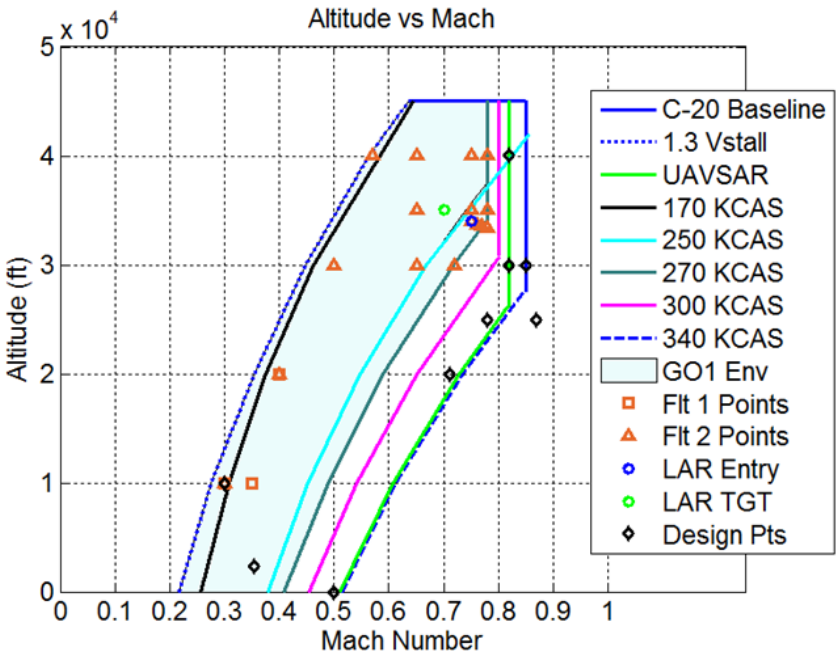


Launch Abort Maneuver:

- **Establish 0.05M below desired entry Mach (i.e. 0.73M for 0.78M entry)**
- **Set 500-deg TGT throttle setting and begin level acceleration to entry Mach**
- **At entry Mach number, initiate 2.0g pull to capture required pitch attitude**
- **Stabilize at 1.0g w/i ±1.0 sec of simulated release point**
- **Execute normal "nose-high recovery" maneuver**
- **Throttles remain fixed from initial acceleration to acceleration on recovery**

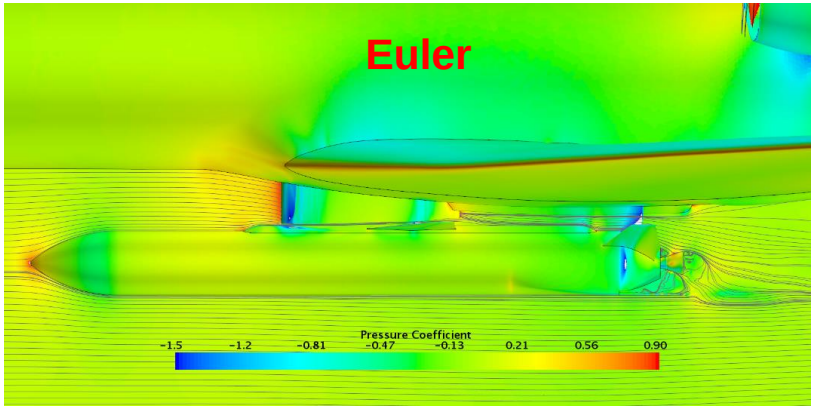
Flight Test Plan

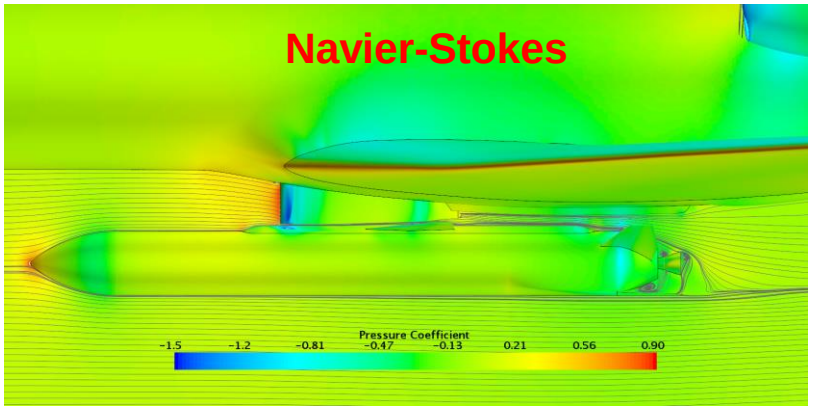
- **A build-up approach was undertaken to incrementally increase dynamic pressure and g-loading on the ITA**
- **The envelope was cleared to the extent required to perform the launch abort and recovery maneuver**
- **Flight Test Maneuvers:**
  - **Steady Level Flight** – Structural Dynamics Assessment
  - **Steady Heading Sideslips** – Controllability Assessment
  - **Angle Captures** – Controllability Assessment
  - **Push Over Pull Up** – Loads Assessment
  - **Raps** – Structural Dynamics Assessment



Aerodynamics and Propulsion Analyses

- **Aerodynamics deltas of the GO1-ITA store were shown to be small and within the aerodynamic variations of the legacy/flown UAVSAR pod**
  - Analysis indicated possible issues with high-speed flight at Mach 0.82 and above
- **Aero loads were developed using the worst-case combination of Euler and Navier Stokes CFD, and were run at multiple flight conditions**
- **The C-20A aircraft engine operation and potential stagnation issue at the high-altitude and low-speed portion of the GO1-ITA's aircraft recovery flight envelope was assessed**
- **Aircraft landing gear close proximity and aerodynamic interferences during take-offs and landings were assessed**





GIII Simulator and Controls/HQ Analysis

- An engineering simulation, which models the GIII flight dynamics, was developed and validated for a prior flight project
- ITA aero and mass property models were implemented into the simulation
- Simulation was used to hone in on the ideal entry conditions for performing the release maneuver
- Simulator provided aircraft dynamics for assessing ITA inertial loads
- Project confirmed that the captive carry configuration did not cause any unacceptable degradation in aircraft stability and Handling Qualities (HQs)

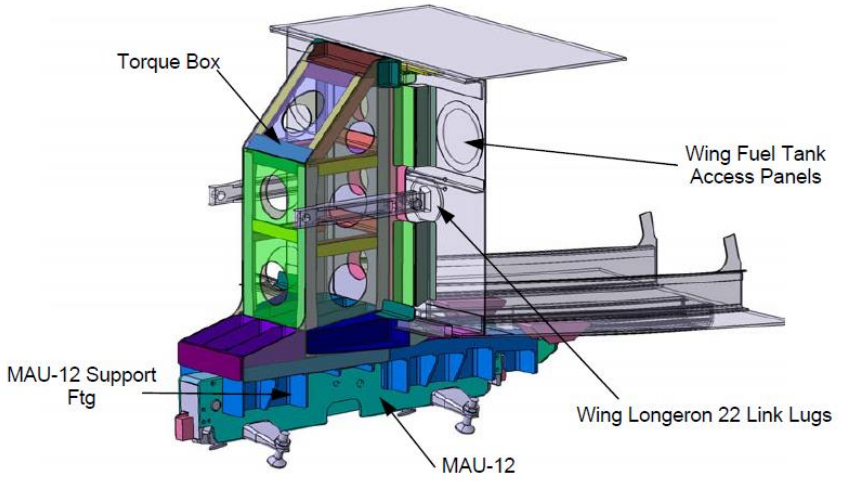
Structures Analysis

- **Aero loads were developed using the worst-case combination of Euler and Navier Stokes CFD, and were run at multiple flight conditions (by varying qbar, α, and β)**

- **ITA inertia forces & moments (including raps and launch abort recovery maneuvers) were obtained from the AFRC G-III simulator and Adaptive Compliant Trailing Edge flight data**

- **The GO1-ITA structural analysis, design and as-built drawings, work orders, and material certifications provided by Generation Orbit were reviewed and validated**

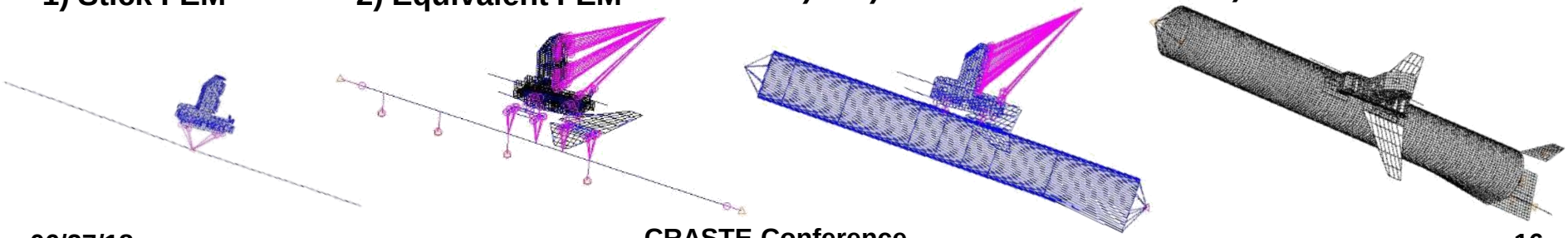
- **ITA Design Factors of Safety on Ultimate:**
  - **No testing required**
  - **Metallic: 2.25**
  - **Composite: 3.0**



Structural Dynamics Analysis

- **Finite Element Model (FEM) Development**
  - Multiple ITA FEMs were created with increasing complexity over the project life cycle
- **Ground Tests**
  - C-20 + ITA Ground Vibration Test (GVT) – July 2017
  - Moment of Inertia (MOI) Test at GO's facility – Oct. 2017
  - ITA *mini*-GVT Checkout – Nov. 14, 2017
  - ITA GVT rigid body frequencies were very close together (within ≈ 1 Hz) & much lower than UAVSAR
- **Flutter Analyses of GIII + ITA**
  - Multiple GIII+ITA flutter analyses have been performed over the project life cycle as complexity of the FEM increasing and as FEM was updated with GVT & later MOI data
- **Flight Flutter Testing**
  - Supported flight planning & supported flights

1) Stick FEM **2) Equivalent FEM** **3) & 4) Detailed FEM** **5) Full Detailed FEM**

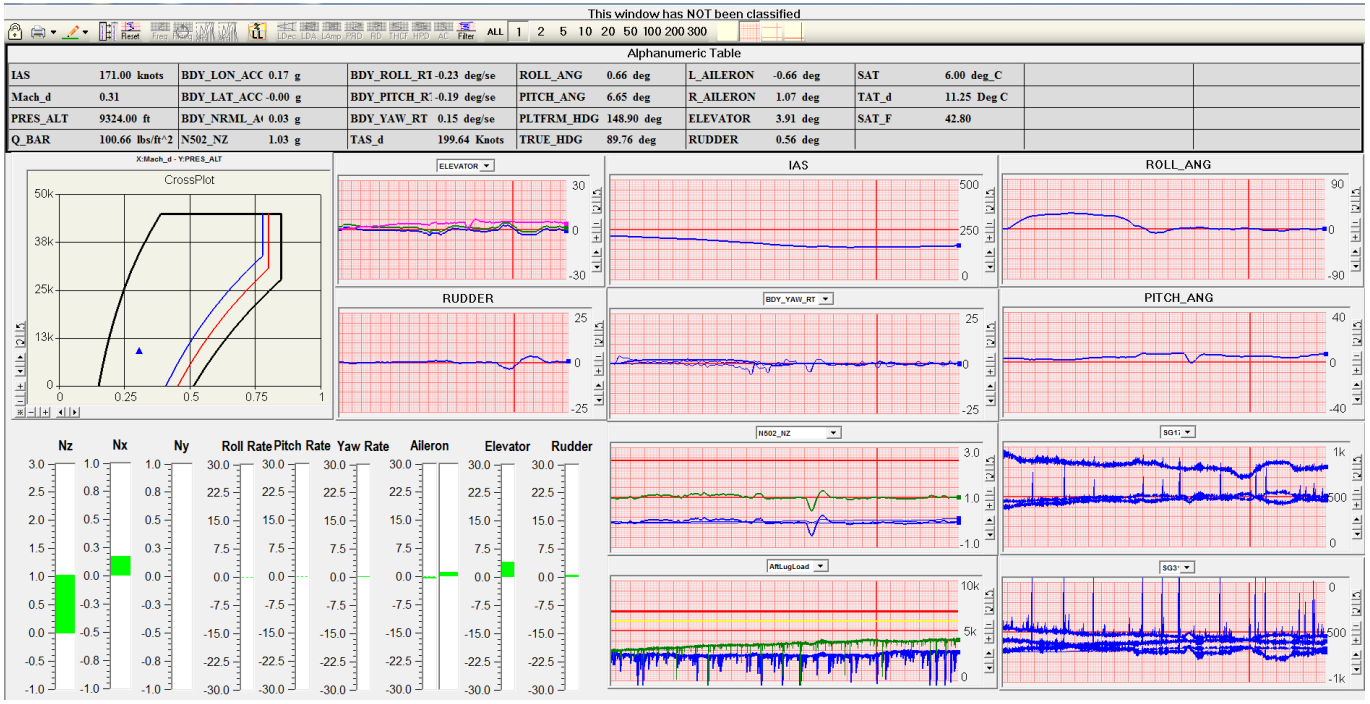


Instrumentation and Data Displays

- **The project used a S-Band Quasonix EVTM transceiver.**

- **Real-time telemetry data was processed and recorded on the ground. The onboard data was archived post flight**

- **Real-time data was viewed in the control room using Interactive Analysis and Display System (IADS)**



Ground Testing

- **Ground Vibration Testing – important for FEM model verification in support of flutter analysis**
- **Moment of Inertia Testing – verified loads, dynamics, and simulator models**
- **Loads and Deflection Test – verified structures analysis and instrumentation**
- **ITA Telemetry Checks – verified data transmission prior to aircraft integration**
- **C-20 and ITA Telemetry Checks – verified data transmission prior to Combined System Test**
- **Combined System Test – verified integrated system prior to first flight**

Flight Testing

- **The project completed a high speed taxi test and three flights**
- **The third flight was dedicated to completing the launch abort release maneuver starting with a 15 degree pitch attitude and building up to the 30 degree pitch attitude**
- **The launch maneuver objective of a pitch-up to 30degs at Mach 0.70 and an altitude of 35,000ft was completed during a third flight on December 12, 2017**

Pilot Comments

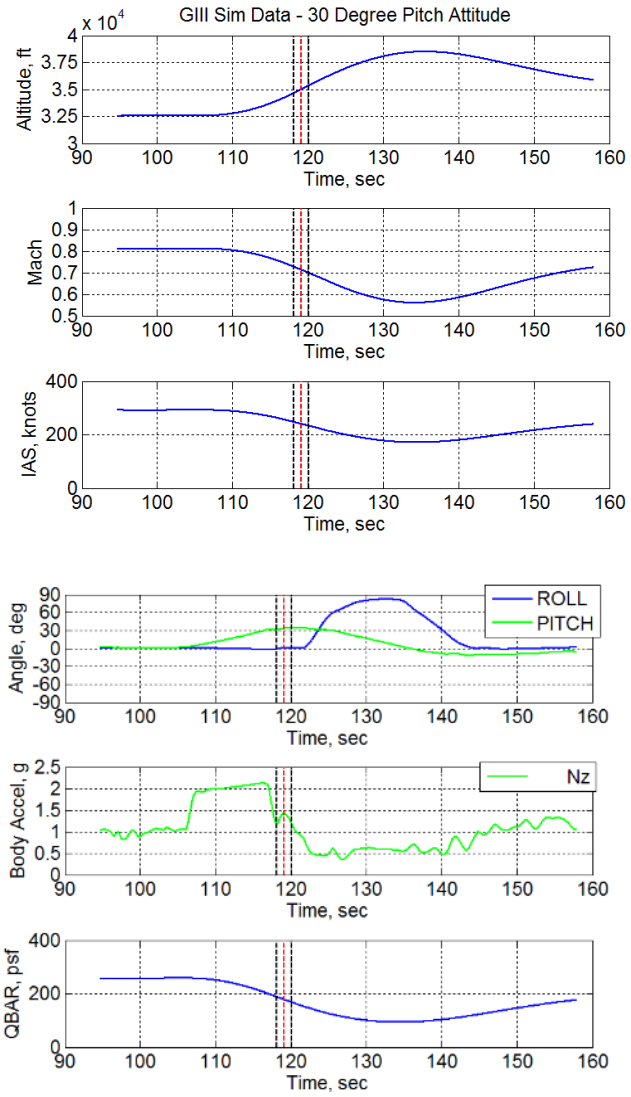
- **Rotation forces at takeoff not as noticeable as for UAVSAR pod**
- **During rolling maneuvers (a.k.a. bank-to-bank rolls), ITA presence noticeable**
  - Pendulum effect
  - Slight bank overshoot
- **Simulator gave a good representation of maneuver, to include roll rates, yoke forces, and energy planning**

- **Executed 'flight abort maneuver' from multiple pitch angles**
  - 15, 20, 25 and 30 degrees pitch
  - 15/20 degree pitch maneuvers very similar to mild "upset" training
  - 25/30 degree pitch maneuvers higher attitude than *normal* but very controllable
- **Four 30-deg / 0.70 M abort maneuvers flown**

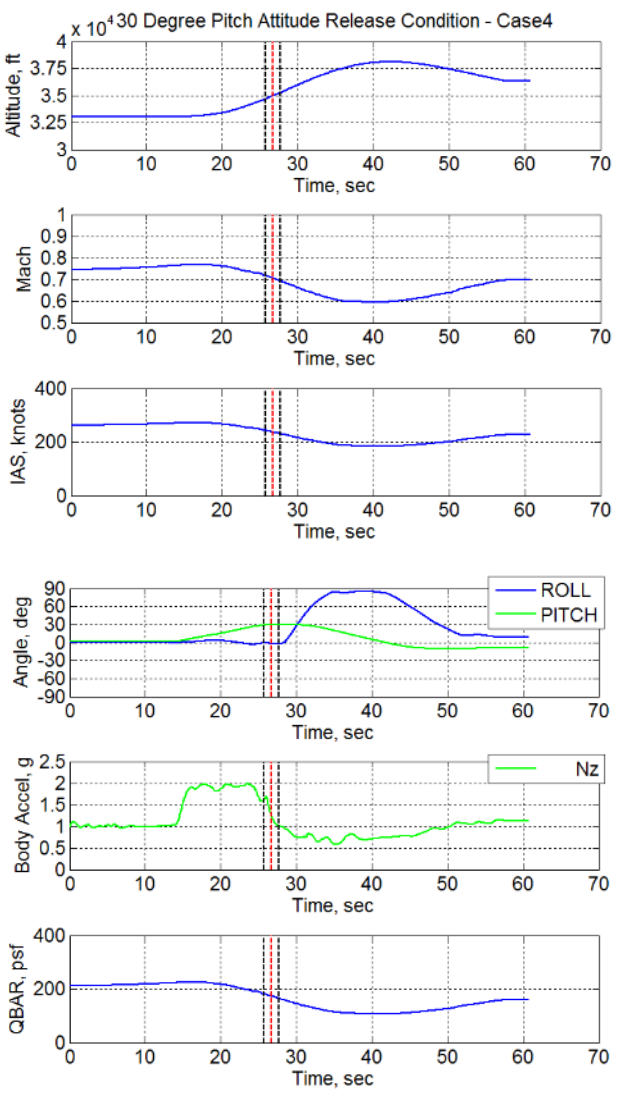
Entry Altitude	Mach at Pull-up	Mach at FL350	Pitch at Release
33,400 ft	0.77	0.71	28-deg
33,300 ft	0.75	0.69	33-deg
33,200 ft	0.75	0.68	30-deg
33,100 ft	0.77	0.70	30-deg

GIII Sim vs Flight

GIII Sim



Flight



Pilot Comments, cont'd

- **Leaving throttles fixed throughout maneuver was a good idea**
  - A level accel 0.05M below entry airspeed resulted in stable engine power
  - 500-deg TGT setting gave good recovery airspeed
- **Release airspeed sensitive to pull-up 'g'**
  - Need g-meter
  - 2.0-g resulted in good climb performance and was very repeatable
- **Recovery airspeed was always safe as long as no delay in rolling to 90-deg bank at recovery**
  - "Crisply" roll to 90-deg bank
  - Even slight delays resulted in 10-20 knot recovery airspeed differences
  - Never approached stick shaker
- **Summary**
  - Maneuver was simple and repeatable
  - The simulator was an excellent tool in preparing for the profile
  - The ITA appeared to have less drag in-flight than in the simulator

Conclusions and Project Challenges

- **The project completed the primary goal of integrating the ITA onto the C-20 and performing the launch maneuver at a 30 degree pitch up at a 0.70 Mach and an altitude of 35,000ft on the third flight**

- **Challenges:**
  - Managing expectations between a startup company culture and government culture
  - Managing scope increase for a small budget project
  - Getting a team with the right skillsets pulled together and up to speed on a short term project
  - Maintaining an appropriate level of oversight with a company with no prior working relationship
  - Tailoring the airworthiness process appropriately to efficiently meet the goals of the project